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STRENGTH OF SHORT FIBER REINFORCED COMPOSITES

BY

R. E. LAVENGOOD

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28

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13. ABSTRACT

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FOREWORD

The research reported herein was conducted by the staff of the Monsanto/Washington University Association under the sponsorship of the Advanced Research Projects Agency, Department of Defense, through a contract with the Office of Naval Research, N00014-67-C-0218 (formerly N00014-66-C-0045), ARPA Order No. 876, ONR contract authority NR 356-484/4-13-66, entitled "Development of High Performance Composites."

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STRENGTH OF SHORT FIBER REINFORCED COMPOSITES

R. E. Lavengood

ABSTRACT

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STRENGTH OF SHORT FIBER REINFORCED COMPOSITES

R. E. Lavengood

Introduction

There is currently a growing interest in composites reinforced with a two dimensionally random array of fibers. This is due in part to the expanding use of random mat and sheet molding compounds and also to the design simplifications permitted by the planar isotropy of these materials. The elastic properties of random composites have been investigated previously and can be readily predicted (1). The ultimate properties are subject to much more variation and yet have been studied less. The purpose of this investigation is to determine the potential strength of epoxy reinforced with randomly oriented glass fibers and to compare their structural utility with similar composites reinforced with aligned fibers.

Specimen Preparation

Random composites were prepared by vacuum impregnating Owens-Corning M-700 random glass fiber mat. Two matrix resins were used. The first, Epon 828* plus 20 phr Curing Agent 2*, is a relatively brittle material typical of the epoxy matrices normally used in fiber glass composites. The second, Epon 815* plus 66 phr Versamid 140**, is a more ductile resin which was

*Shell Chemical Co.

**General Mills

found in earlier studies to give better transverse composites and crossplies (2). The resin and curing agent are mixed thoroughly at room temperature and then heated to 50°C to reduce the viscosity. The water-like mixture is poured into a 2" x 6" compression mold which is preheated to 90°C. Four layers of random mat are placed on top of the resin and the mold is placed in a 90°C vacuum oven at 0.1 mm hg. for 20 minutes. The top of the mold is then put in place and the composite pressed for 30 minutes at 100°C and 40 psi followed by 60 minutes at 120°C and 100 psi. This rather complicated process was devised to produce specimens with very low void content and thoroughly wetted interfaces. The actual void content was below the resolution limit of the commonly used gravimetric technique. The transparency of the 1/8" thick, 20 v/o sample shown in Figure 1 is probably the best indication of the overall quality of this material.

The aligned fiber samples were prepared by extruding molding compound into oriented, "B" staged, rods and then compression molding the rods. The matrix resin was Epon 828 plus 30 phr methylene dianiline. This material has mechanical properties similar to those of the 828/2 used with the random systems. The molding compound contained 50 volume percent of 1/8 inch long glass fibers. This loading level and the fiber length were shown in earlier studies to give optimum properties in flow molded specimens.

More specific details about the preparation of the molding compound are given in Reference 4.

Tensile specimens were 1/2 inch wide strips, 6 inches long, with a 3 inch gage length. A constant crosshead speed of 0.02 inches per minute was used and strains were monitored with a 2 inch strain gage extensometer. All tests were run at 23°C.

Test Results and Discussion

Typical tensile stress-strain curves for composites with different volume fractions of glass fibers are shown in Figure 2. The curves for the filled materials are all essentially linear to failure and all terminate between one and two percent elongation.

The effect of fiber volume fraction on strength is shown more clearly in Figure 3. The line is a least squares fit of the data and serves to emphasize the linear increase in strength with increasing volume fraction. The equation of this particular line is

$$\sigma = 10.5 + 59.6 \phi \quad (1)$$

where σ and ϕ are strength and fiber volume fraction, respectively.

Existing theories predicting the strength of random composites are based on the assumption that strength is an additive property. This implies that the strength of a random composite will be equal to the average of the strength vs. orientation angle for a similar unidirectional composite. This approach seems to have been originated by Horio and Onogi (5) who

used an improper transformation equation to derive the following expression:

$$\sigma = (\sigma_l \sigma_t)^{1/2} \quad (2)$$

where σ_l and σ_t are the longitudinal and transverse strengths of an equivalent unidirectional composite.

More recently, Lees (6) derived the following equation:

$$\sigma = \frac{2\tau}{\pi} \left(1 + \frac{\sigma_t}{\sigma_m} + \ln \frac{\sigma_t \sigma_m}{\tau^2} \right) \quad (3)$$

where τ = composite shear strength

and σ_m = matrix stress at ultimate composite elongation.

With a similar approach, Chen (7) concludes that the predictive equation should be:

$$\sigma = \frac{2\tau}{\pi} \left(2 + \ln \frac{\xi \sigma_c \sigma_m}{\tau^2} \right) \quad (4)$$

where σ_c = the rule of mixtures strength for an equivalent unidirectional composite

ξ = a strength efficiency factor which relates the strength of a unidirectional short fiber composite to the rule of mixtures prediction.

Evaluation of these equations is complicated because all the terms vary with volume fraction. The calculation of σ_c is straightforward and, for an upper bound approximation, we can let ξ equal to one. An estimate of σ_m can be obtained from the data in Figure 2. The last two terms are more difficult to estimate; however, it has been shown that τ and σ_t are

about the same for glass epoxy composites. While there are no reliable techniques for predicting σ_t , the transverse strengths of composites with a similar matrix are available in the literature (8,9). The values of σ_c , σ_m , and σ_t , thus determined, are listed in Table 1. These were substituted into equations 2, 3 and 4 to obtain the curves shown in Figure 4. These may be compared with the curve for equation 1, which represents the experimental data. It is apparent that equations 2, 3 and 4 do not adequately predict the strength of these composites.

The series of composites with Epon 815/Versamid matrix was prepared with the expectation that the ductility of the matrix and the improved adhesion would lead to higher strength composites. The experimental results in Figure 5 show that this did not occur. The strengths of the composites are essentially the same for both matrices. This implies that the fracture is not initiated by failure of the matrix or interface. The other possible source of crack initiation is tensile fracture of the glass fibers.

Fiber stress will be greatest in those fibers which are aligned with the axis of the specimen. Since glass is linearly elastic to failure, the ultimate stress of these fibers can be estimated as follows:

$$\sigma_g = E_g \epsilon_c \quad (4)$$

where σ_g = maximum fiber stress

E_g = modulus of the fibers (i.e., 10.5×10^6 psi)

and ϵ_c = ultimate composite strain.

The data for the 828/Z composites were used to calculate the fiber stress values shown in Figure 6. The apparent strength of most of these fibers is between 150 and 200 ksi. The maximum value of 220 ksi is about 60% of the strength normally associated with E glass roving and is reasonable for glass that has been chopped (by the manufacturer) and converted to mat. The tendency for the fiber strength to decrease with increasing volume fraction can be attributed to the fiber damage due to compaction during the molding cycle.

This behavior is in striking contrast to that of composites reinforced with aligned short fibers. A previous study of composites in which the reinforcing fibers were oriented by flow processing showed that the strength of such materials does not reflect fiber strength. The completely different fracture patterns characteristic of random and aligned systems are shown in Figure 7. The crack propagates directly across the random fiber specimen, normal to the applied stress, as if the material were homogeneous. Both fibers and matrix are broken in the process. The jagged fracture surface of the aligned system results from a crack propagating along and between fibers which are slightly misoriented (3). In this case, the fracture is confined to the matrix and interface so the strength of the glass fibers cannot contribute directly to composite strength.

The longitudinal strength of composites with oriented fibers is shown in Figure 8 along with the "least squares" line for the strength of random composites (i.e., Eq. 1). Over the entire range of volume fractions, the strength of the composites are about the same for both orientations. This unexpected result must be regarded as fortuitous since the failure mechanisms are so different.

Despite the above result, from a strength viewpoint the structural utility of these composites is not the same because of the anisotropy of the unidirectional composites. The low transverse strength of such materials greatly complicates design when multiaxial loads are present. Strength as a function of angle for random and aligned composites with 50 volume percent fibers are compared in Figure 9. Although the strengths are similar in the axial direction, the random composites are clearly superior in all other directions. Specifically, the transverse strength of the oriented composites is less than 1/6 that of the random composites.

A comparison of the potential usefulness of these composites must also consider their relative stiffnesses, and again anisotropy is important. The modulus as a function of angle for the same 50 volume percent random and aligned composites is shown in Figure 10. In this case neither of the composites is clearly superior. The tensile modulus of the random system is about two-thirds the longitudinal and twice the transverse modulus of the unidirectional

material. The preference for one material over the other, on the basis of modular properties, would therefore depend on the application. In uniaxial applications the oriented material would be superior, while multiaxial applications would favor the random composites.

Summary and Conclusions

The strength of composites reinforced with randomly oriented glass fibers increases linearly with volume fraction. Maximum strengths of 35 to 42 ksi are achieved with 50 volume percent fibers. At loading levels above 50 percent the strength decreases due to extreme fiber damage. For all loading levels, the strength of the random composites is somewhat greater than that of equivalent composites in which the reinforcing fibers were aligned by flow processing. This, coupled with the planar isotropy of the random composites, makes them superior to the aligned system for all strength limited applications. Composites with aligned fibers are best suited for uniaxial situations in which the high longitudinal stiffness can be utilized.

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10

TABLE 1

v/o	σ_c	σ_m	σ_t
0	10.5	10.5	10.5
10	34.5	--	4.0
20	58.5	4.9	4.2
30	82.4	4.6	4.3
40	106.3	4.5	5.4
50	130.3	4.1	5.5
60	154.2	3.0	6.4

LIST OF FIGURES

- Figure 1. Typical 1/8" thick composite containing 20 volume percent of random glass fiber.
- Figure 2. Typical stress-strain curves for composites showing the effect of filler loading level on mechanical performance. The numbers at the ends of the curves indicate the volume percent of glass fibers.
- Figure 3. Tensile strength of composites with 828/Z matrices and varying volume fractions of glass fiber reinforcement.
- Figure 4. A comparison of experimental data (Eq. 1) with predictive equations for the strength of random composites.
- Figure 5. Tensile strengths of composites with 815/V-140 matrices and varying volume fractions of glass fibers.
- Figure 6. Maximum fiber stress developed in composites with 828/Z matrices.
- Figure 7. Typical fracture patterns for (a) randomly oriented and (b) aligned fiber composites.
- Figure 8. Longitudinal strength of unidirectional short fiber composites compared with the strength of similar material with random orientation (i.e., Eq. 1).
- Figure 9. Tensile strength vs. angle for comparable composites reinforced with random and aligned fibers.
- Figure 10. Stiffness vs. angle for comparable composites reinforced with random and aligned fibers.

72

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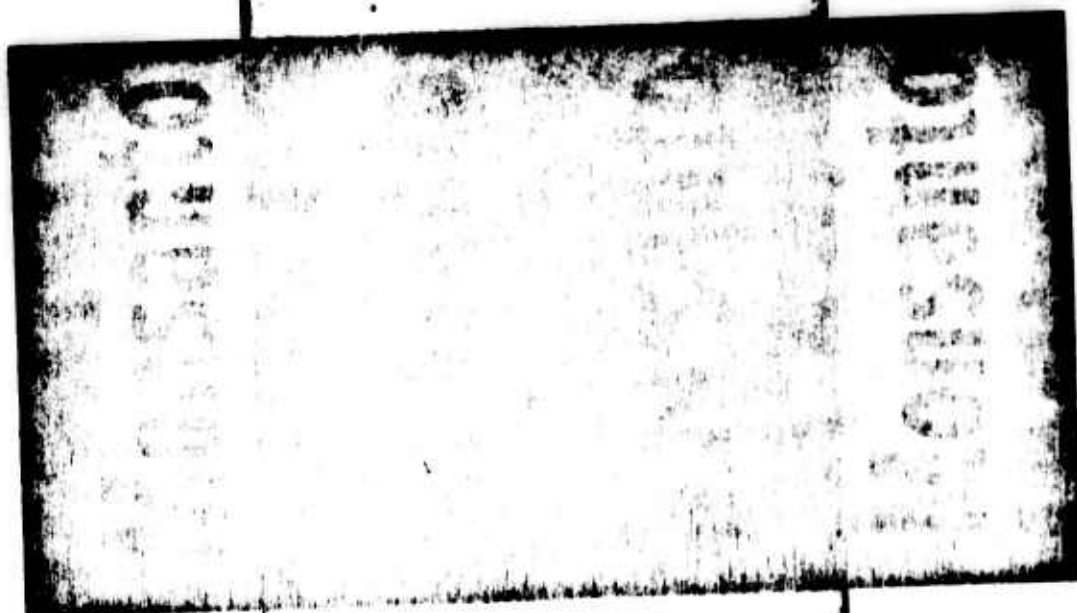


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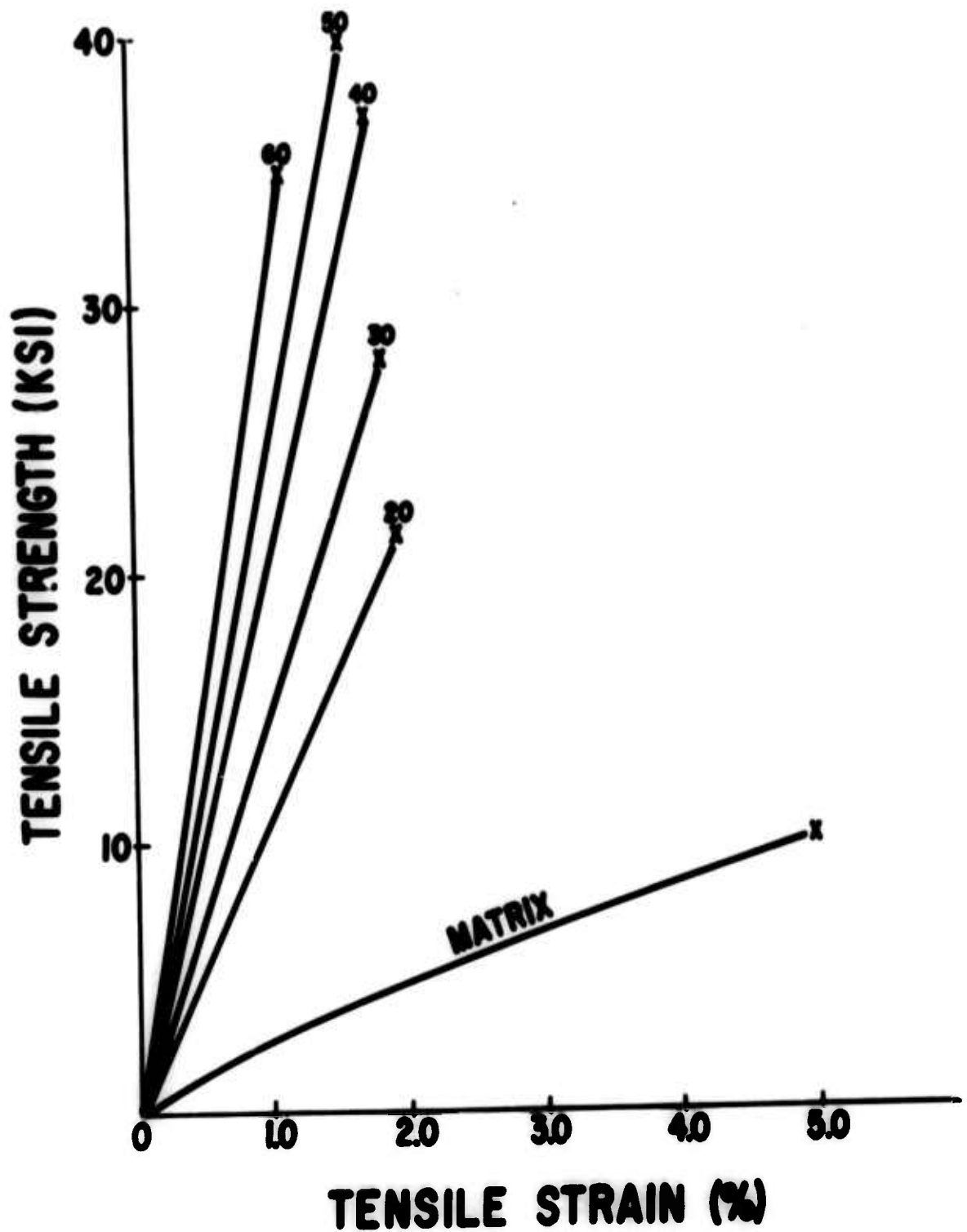


Figure 2. Typical stress-strain curves for composites showing the effect of filler loading level on mechanical performance. The numbers at the ends of the curves indicate the volume percent of glass fibers.

14

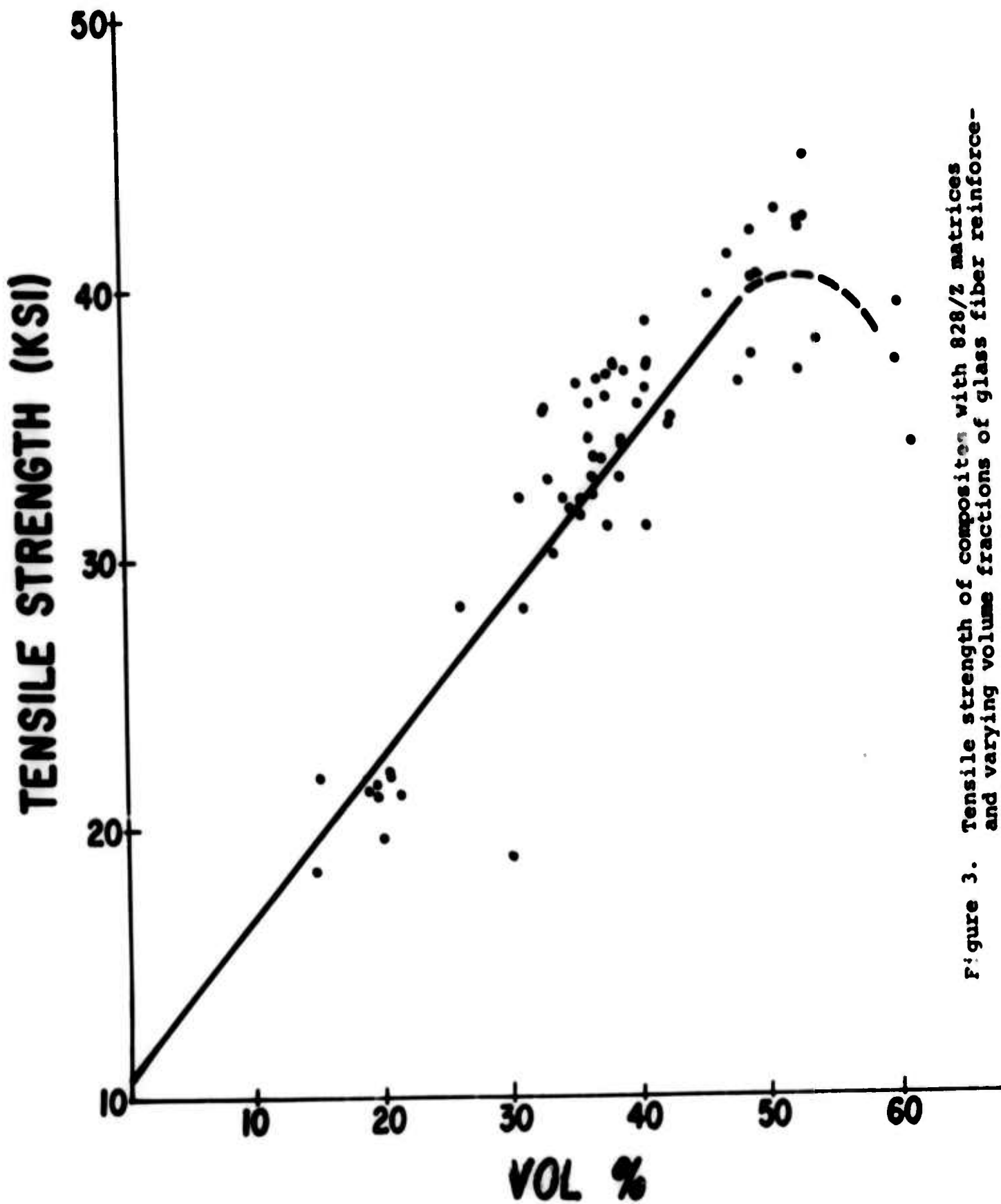


Figure 3. Tensile strength of composites with 828/2 matrices and varying volume fractions of glass fiber reinforcement.

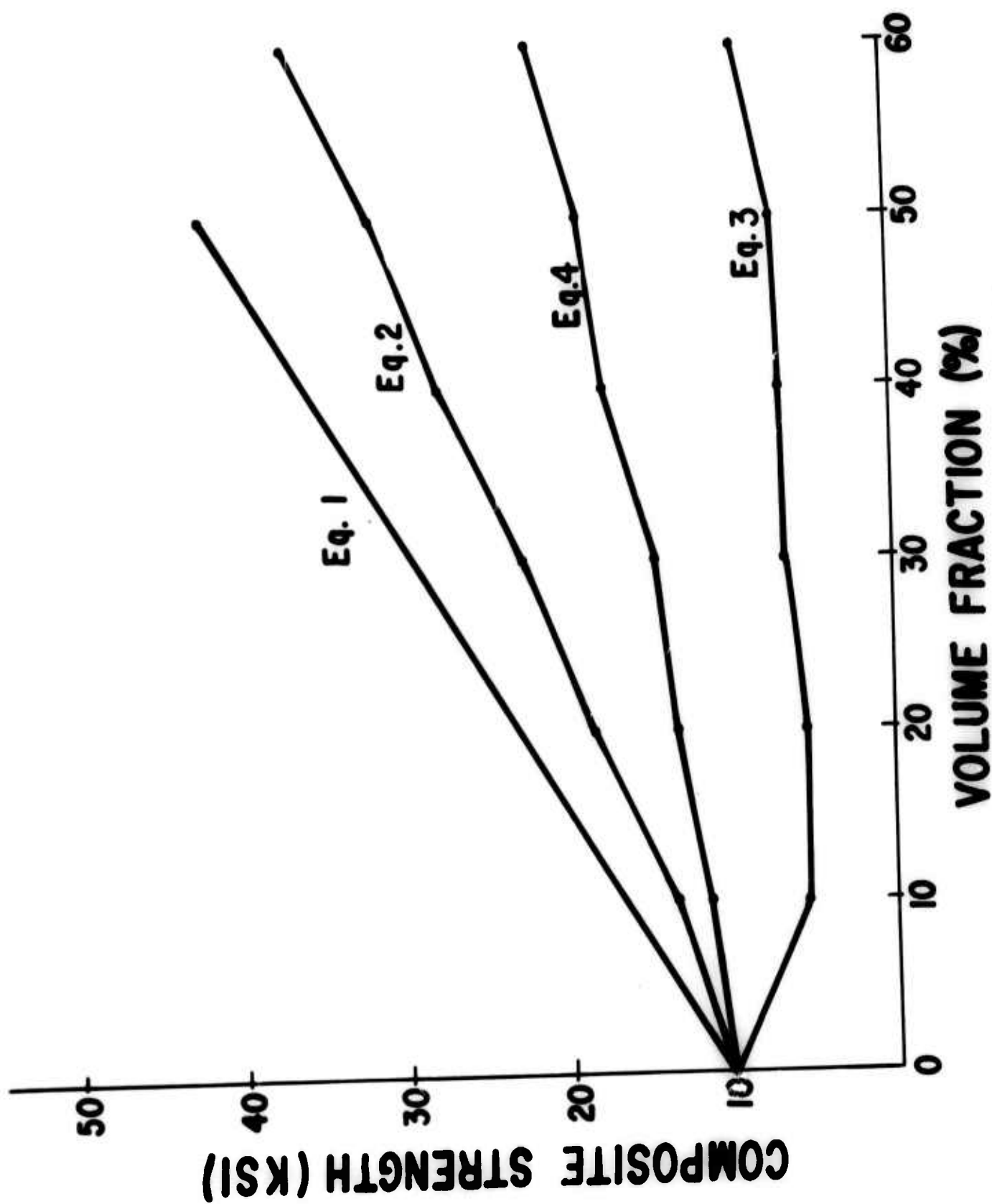


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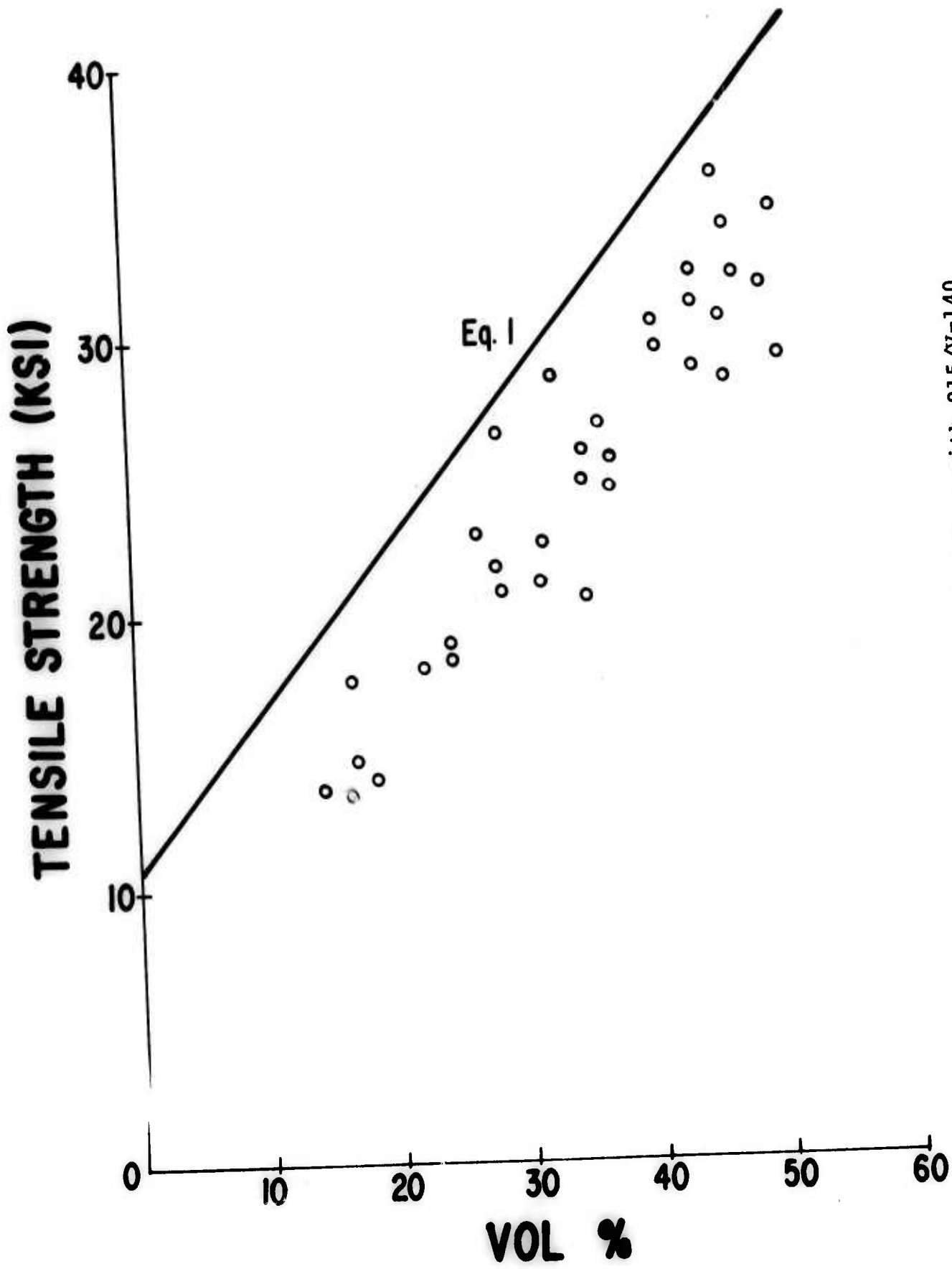


Figure 5. Tensile strengths of composites with 815/V-140 matrices and varying volume fractions of glass fibers.

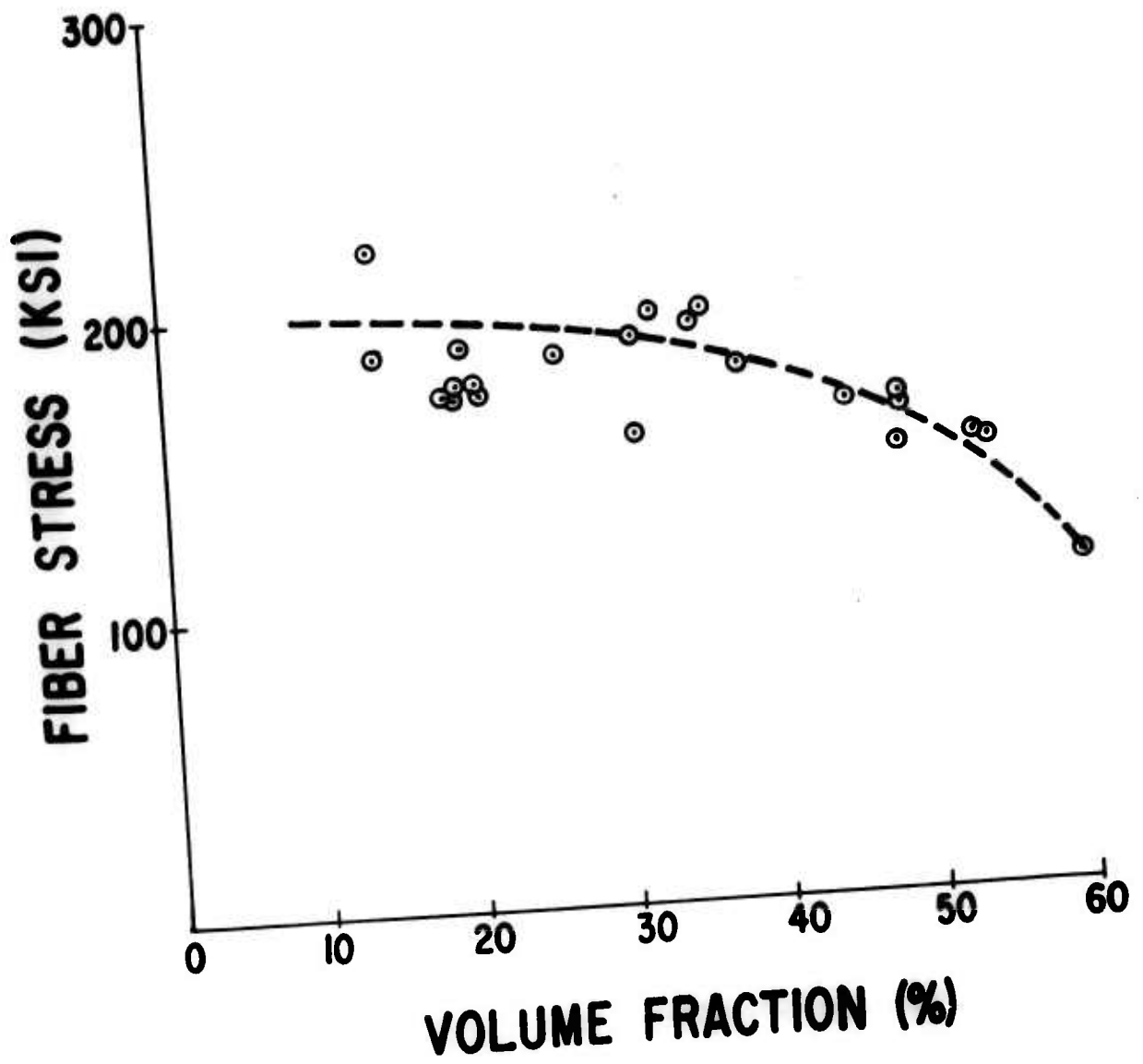


Figure 6. Maximum fiber stress developed in composites with 828/Z matrices.

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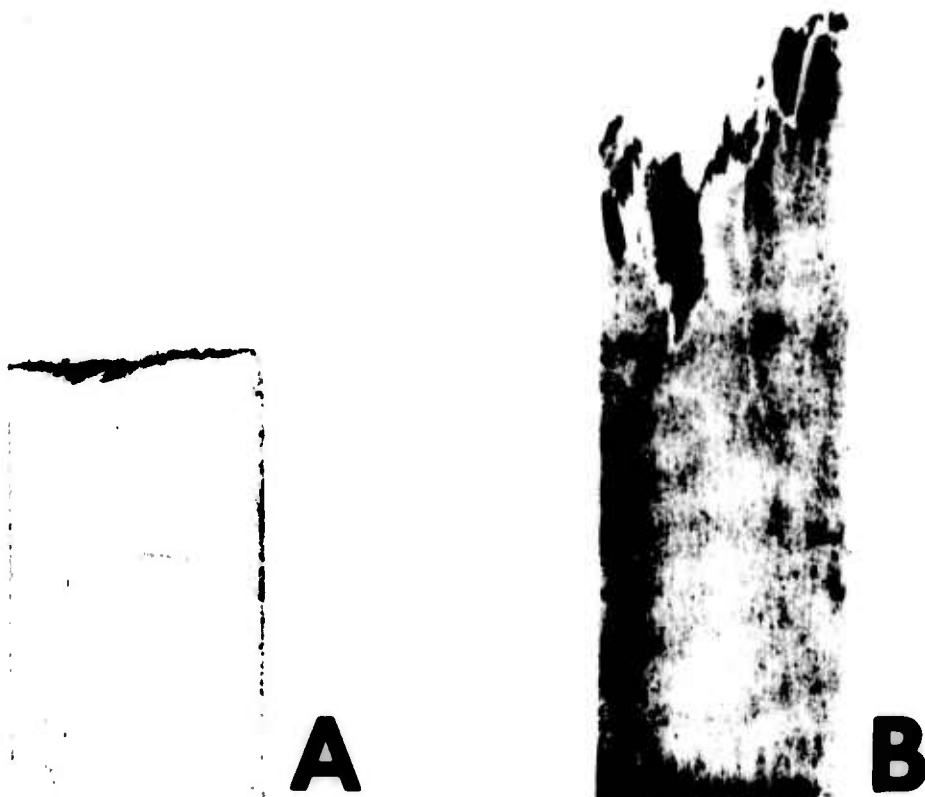


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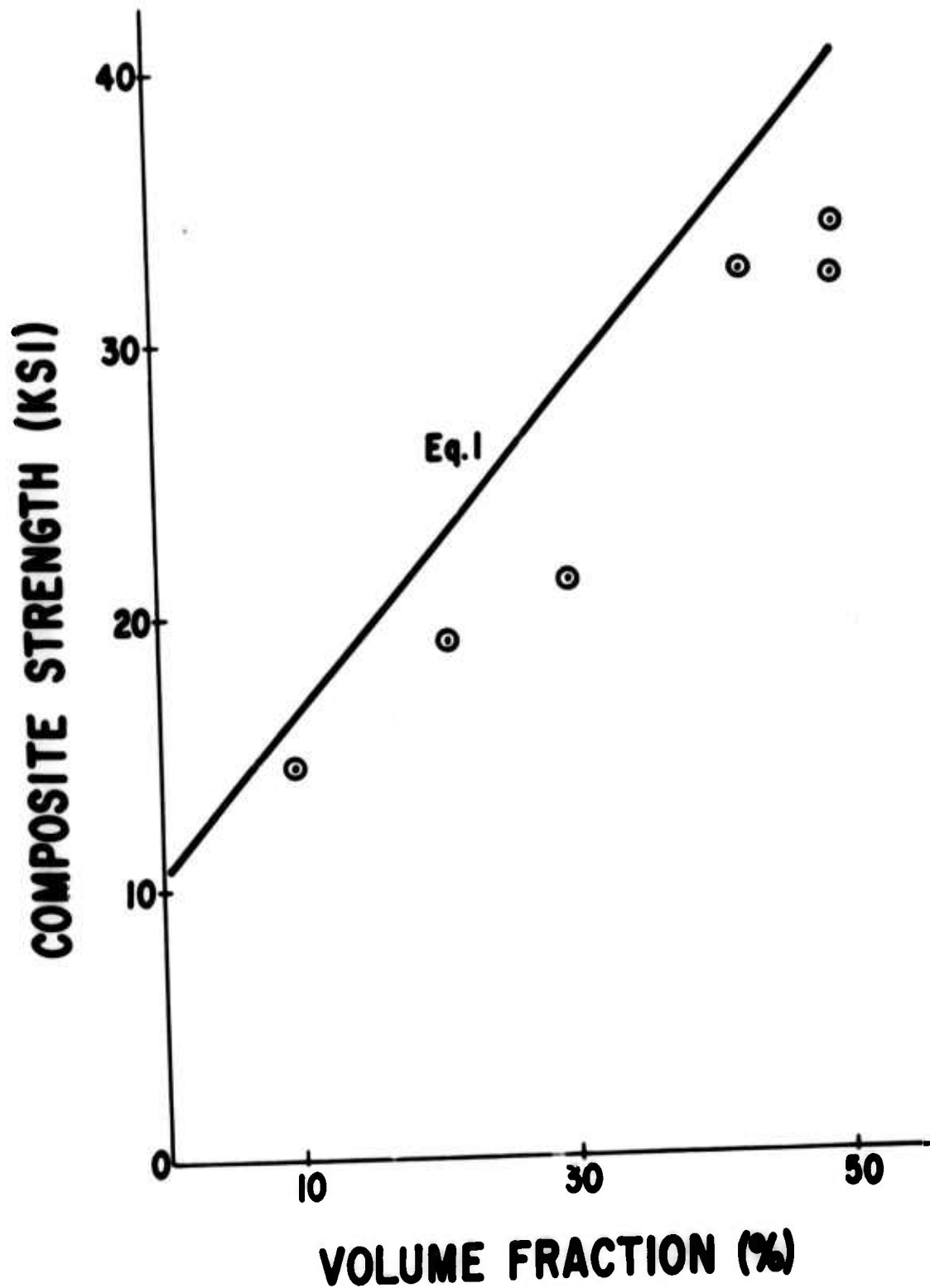


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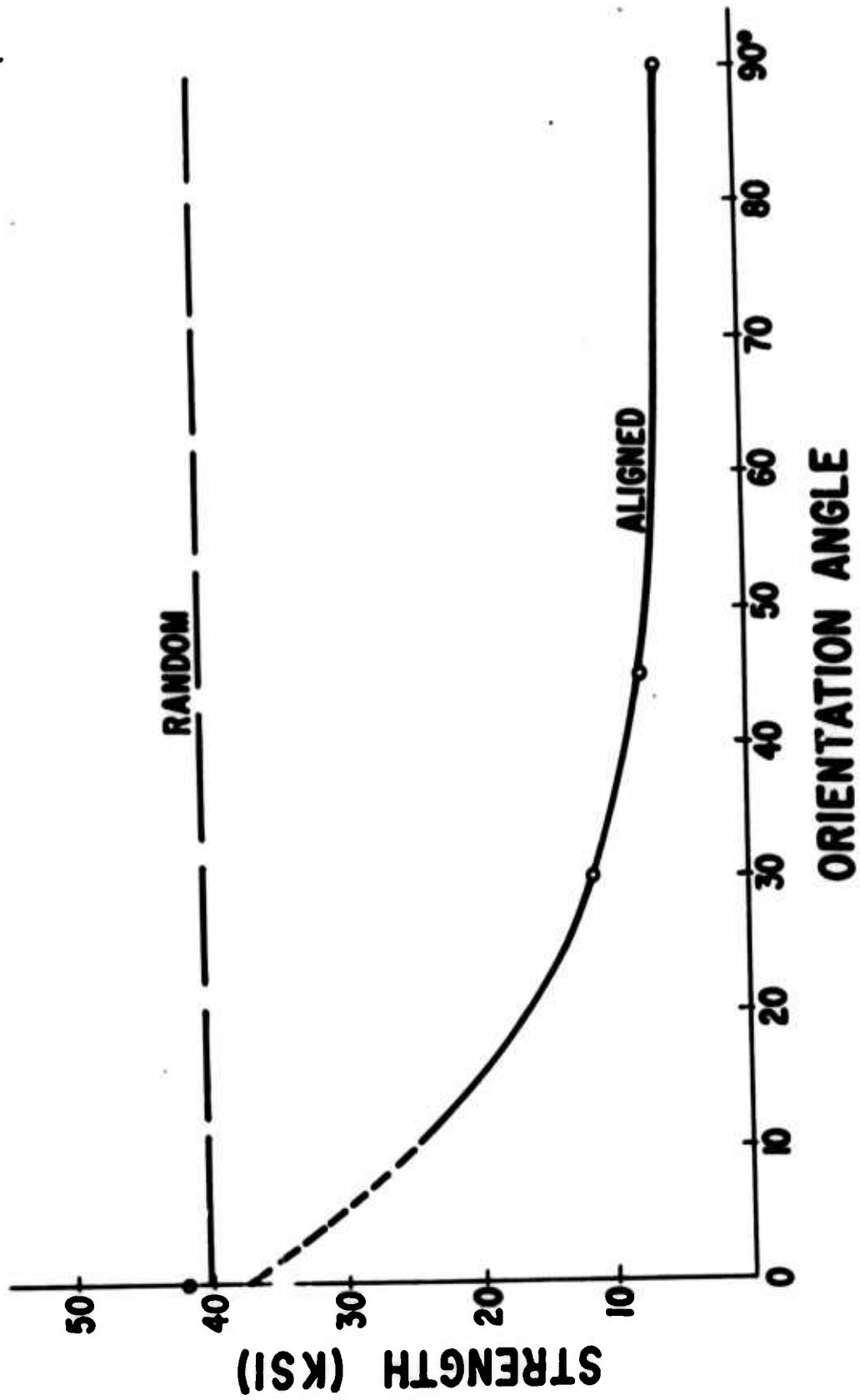


Figure 9. Tensile strength vs. angle for comparable composites reinforced with random and aligned fibers.

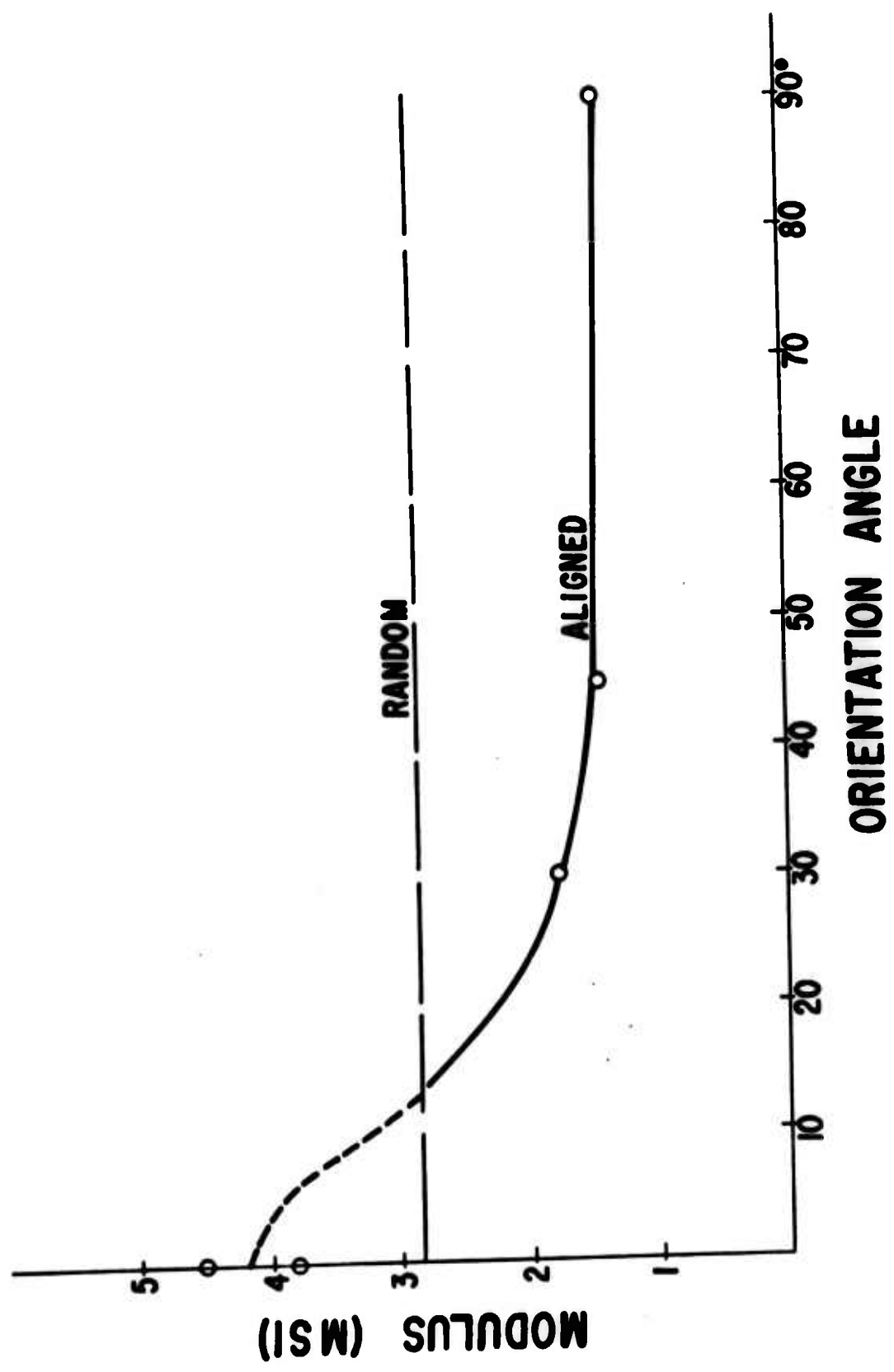


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